A Full Field Transmission X-ray Microscope as a tool for High-Resolution Magnetic Imaging

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***Abstract*—The XM-1 soft x-ray microscope is a user-dedicated facility located at the Advanced Light Source at Lawrence Berkeley National Laboratory and has recently been established as a tool for high-resolution imaging of magnetic domains. It is a conventional full field transmission microscope which is able to achieve a resolution of 25 nm by using high-presicion zone plates. It uses off-axis bend magnet radiation to illuminate samples with elliptically polarized light. When the illumination energy is tuned to absorption edges of specific elements, it can be used as an element-specific probe of magnetism on the 25 nm scale with contrast provided by magnetic circular dichroism. The illumination energy can be adjusted between 250-850 eV. This allows magnetic imaging of elements including chromium, iron and cobalt. The spectral resolution has been shown to be E/ΔE = 500 – 700. This spectral resolution allows a high sensitivity so that magnetization has been imaged within layers as thin as 3 nm. Since this is a photon based magnetic microscopy, fields can be applied to the sample even during imaging without affecting the spatial resolution. The current system can apply in-plane or out-of-plane fields of a few kOe.**

***Index Terms*—high-resolution, magnetic imaging, x-ray microscopy.**

I. INTRODUCTION

The XM-1 X-ray microscope is located at the Advanced Light Source and provides high spatial resolution imaging of samples. The design allows a high throughput of a variety of samples in a wide variety of applications including Biology, Environmental Science, Materials Science, and Magnetic Imaging [1,2,3].

Magnetic imaging is accomplished by transmission through the sample with elliptically polarized light. The large contrast for magnetic materials is provided by x-ray magnetic circular dichroism (X-MCD). This allows element-specific imaging of the magnetization within samples with high sensitivity. Since this is a photon based technique, magnetic fields can be applied to the sample during imaging without affecting the image formation.

The illumination is provided by bend magnet radiation from the Advanced Light Source which is projected onto the sample through a condenser zone plate lens. The present condenser zone plate has a diameter of 9 mm, an outer zone width of 55 nm, and 41,000 zones. The illumination energy can be changed by the linear monochromator, which is composed of the condenser zone plate and a pinhole near the sample plane (typically 100 microns from the sample plane). Due to the chromatic aberrations of zone plates, simply shifting the distance between the condenser and the pinhole/sample plane shifts the illumination energy, which can be changed between 250-900 eV, and has been measured to have a spectral resolution of E/ΔE = 500 - 700 [4].

The radiation passing through the sample is projected through the micro zone plate onto a CCD camera. The present micro zone plate has an outer zone width of 25 nm and a diameter of 63 microns. Both the micro zone plate and the condenser zone plate were fabricated by electron beam lithography by Erik Anderson at the Nanofabrication Laboratory in the Center for X-ray Optics [5].

The high-precision optics allow a high spatial resolution which has been shown to be 25 nm [6]. A series of test patterns with various lines and spaces has been imaged. A test pattern with 25 nm lines and 25 nm spaces can easily be resolved with a contrast of 24 %.

The CCD camera is a 1024 x 1024 pixel array which is back-thinned and back-illuminated. It has a quantum efficiency of approximately 60-70% in the range of energies that the microscope operates.

Samples positions and focus can be pre-selected in a custom Zeiss Axioplan visible light microscope which is mutually indexed with the sample stage of XM-1. X-Y position accuracy is typically 2 microns over a 3 mm field with focal accuracy of 1 micron. This helps to allow the high throughput of samples. During a typical day, hundreds of images are collected.

The field of view of the microscope is 10 microns, so for larger samples, there is an automated montage assembly [7]. This automated process builds a larger image based on a series of subfields. Using cross-correlation techniques, the smaller images are placed at the proper locations creating a nearly

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seamless montage.

II. Magnetic Imaging

X-ray magnetic circular dichroism (X-MCD), i.e. the dependence of the absorption of circularly polarized x-rays onto the projection of the magnetization in a ferromagnetic absorber, can have contrast as high as 25% for element specific core level absorption edges, as e.g. the $L_{2,3}$ edges of transition metals. It has been shown recently that in combination with microscopies like photoemission electron microscopy or soft x-ray microscopy, this can serve as a large contrast mechanism to image the element-specific magnetic domain structure with high lateral resolution [3,8,9]. Working in transmission, the absorption is conveniently measured by recording the transmitted photon intensities. Elliptically polarized light is obtained at the XM-1 from off-axis bend magnet radiation.

A typical example is shown in Figure 1 where the self-organized magnetic domain pattern is shown [6]. It has been obtained in a (0.4 nm Fe/ 0.4 nm Gd) x 75 multilayer system with a pronounced out-of-plane anisotropy. To account for the limited penetration of soft x-rays, it has been prepared onto a 35 nm Si_3N_4 membrane. The dark/light regions correspond to the Fe magnetization with its direction pointing in/out of the paper plane. As expected from the different spin-orbit coupling, the contrast has a reversal between the L_3 and the L_2 edges which is a direct proof of the magnetic character of the pattern observed.

Another magnetic sample studied with XM-1 microscope is 10x(0.3nmCo/1nmPt) multilayers with perpendicular anisotropy, grown on silicon nitride membranes using electron beam evaporation and, patterned by 700 keV N^+ ion beam irradiation through a stencil mask with 1 micron circular holes [10]. The magnetization reversal processes were studied on a nanometer scale by collecting images in the remnant state after various applied fields [11]. The significance of this experiment to our technique is that the high sensitivity allows element-specific imaging of the magnetization of cobalt with only a total cobalt thickness of 3 nm. Figure 2 shows sample after the following magnetization sequence, saturation with +14 kOe (light regions of image), then partial reversal with –4 kOe (dark regions of image). The irradiated regions (circles) have in-plane magnetization, and this has been confirmed by Lorentz Microscopy [12].

This is a photon based magnetic microscopy, thus, in principle, the domain structure can be recorded in unlimited external magnetic fields, which is of outstanding importance e.g. to proof the functionality of current devices, like magnetic sensors, MRAM, etc. The XM-1 is currently able to apply magnetic fields up to a few kOe.

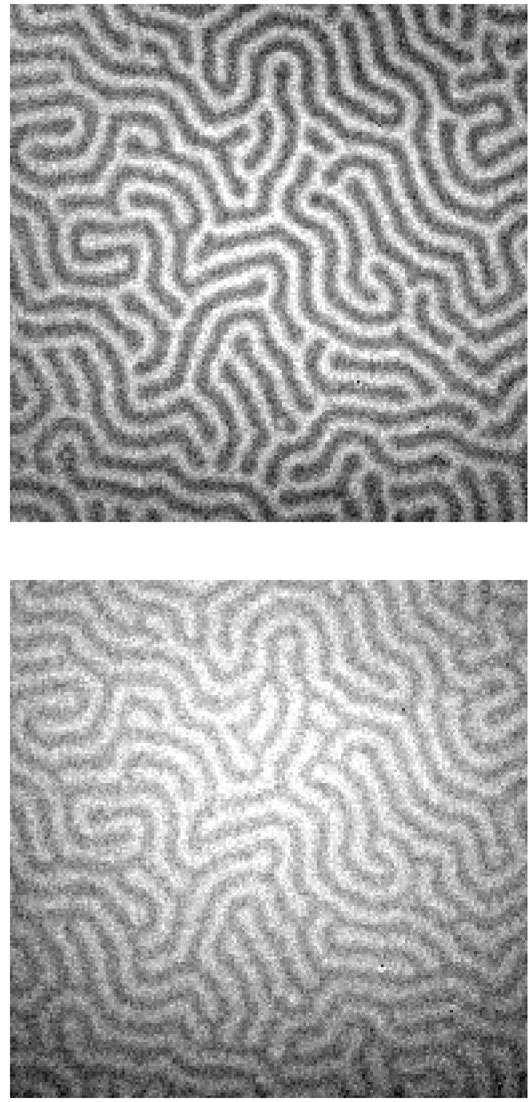

Figure 1. Images of magnetization within an iron gadolinium multilayer, imaged at the iron L_{III} and L_{II} edges (707.5 and 720.5 eV, respectively). The expected contrast reversal of X-MCD between the edges can be seen. The field of view of each image is 5 μm.

Since it is the projection of the local magnetization onto the photon propagation direction providing the contrast, in-plane magnetization, which is the most favorable configuration for magnetic systems of low dimensionality can be addressed by tilting the sample relative to the photon propagation direction. The first results have been recently obtained at the XM-1 [3]. Furthermore, the M-TXM allows to distinguish between in-plane and out-of-plane contributions to the magnetic domain structure. Together with the high sensitivity down to a few nanometers thickness due to the large magnetic contrast this technique allow the study of magnetic microsctructures and the reaction to external fields in current technologically relevant magnetic systems, like magnetic sensors (GMR, TMR), nanostructures, patterned media (MRAM) and high density storage media (magneto-optics).

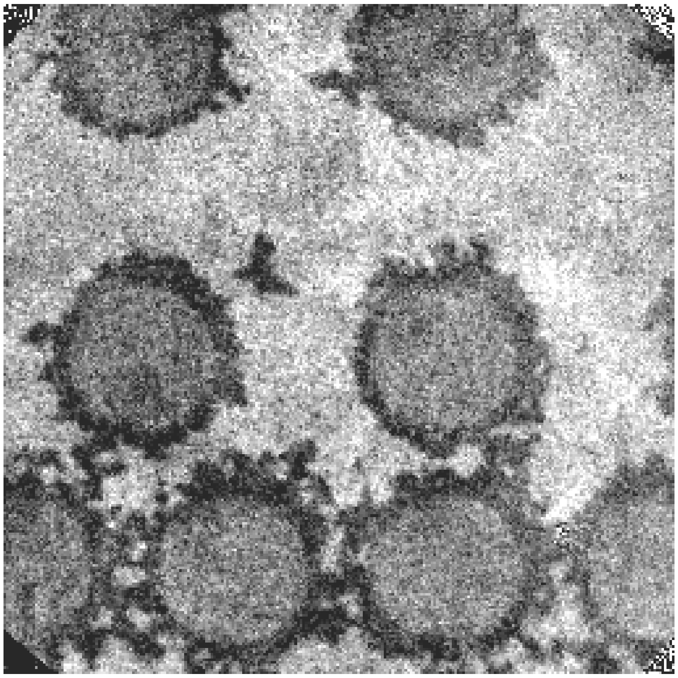

Figure 2. Image of magnetization of irradiation patterned Co/Pt multiplayer. The lightest and darkest regions are out-of-plane magnetization in each direction. The medium circles are the irradiation patterned regions which have in-plane magnetization. The field of view of the image is 4 µm.

III. CONCLUSIONS

High resolution x-ray microscopy with high-precision zone plate lenses can be used as an element-specific probe of the magnetization within samples. The X-MCD contrast mechanism allows high sensitivity to the magnetization of specific elements within a sample. This photon based imaging technique is not affected by applied magnetic fields, so the magnetization within the samples can be imaged even while a magnetic field is applied.

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